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PCC voltage power quality restoring strategy based on the droop controlled grid-connecting microgrid

Wei Feng[1], Kai Sun[1], Yajuan Guan[2], Josep M. Guerrero[2], Xi Xiao[1]

[1] *Department of Electrical Engineering, State Key Lab of Power Systems, Tsinghua University, Beijing, People's Republic of China*
[2] *Department of Energy Technology, Aalborg University, Aalborg, Denmark*
E-mail: fwqqrse@163.com

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Abstract: As the non-linear loads increase along the low-voltage distribution network (LVDN), voltage harmonic components will appear at the point of common coupling (PCC). To improve the voltage power quality of PCC, an active PCC voltage power quality restoring strategy based on droop controlled grid-connecting microgrid (DCGCM) is proposed. The load current of LVDN and the grid-connecting current of DCGCM are sampled and are calculated through an additional PCC voltage restoring controller adopted in the secondary level of system. Then, the generated voltage harmonic reference offset is sent to the primary level and tracked by voltage controlled inverter. In this way, the required harmonic current is injected into the LVDN to supply the nonlinear loads at the cost of slight voltage distortion of DCGCM's output voltage. Therefore, the voltage power quality of PCC can be restored. At last, the simulation results from SIMULINK/MATLAB have been presented to verify the validity of the proposed control strategy.

1 Introduction

Recently, there is a growing concern about the power quality issue because the non-linear loads and power electronics interfaced distributed generations (DG) units are increased along the low-voltage distribution network (LVDN) [1–3], non-linear switch feature, the poor damping of inverter and the random of renewal energy may make conventional LVDN more vulnerable to the oscillation and instability [4, 5].

Some advance control strategies have been reported to decrease the influence of distorted grid to the grid-connecting current (GCC) of independent grid-connecting inverter (GCI) [6–9]. A complicated closed-loop control algorithm for GCI is proposed in [10], in which the harmonic components of GCC are compensated by the outer current controller, and then the power quality of GCC is improved. In [11], the harmonic voltage components were then feed forward to the inner loop of the system, consequently reducing the harmonic GCC of the GCI.

Besides the independent GCI, more microgrids (MGs) established by the paralleled voltage controlled inverters (VCIs) are connected into LVDN for improving local power supplement reliability, as shown in Fig. 1. As more functions and complicated operation modes are required of MG, an advanced MG hierarchical theory is proposed to define system on three levels to facilitate the design of controller according to different functions [12]. However, given that the output equivalent impedance of the droop controlled grid-connecting MG (DCGCM) is similar to the GCI, the effort has also been made to investigate the power quality influence to the system and corresponding improvement control strategies [13, 14]. An active GCC power quality improving strategy when MG connecting to the distorted grid is discussed in [15]; the harmonic GCC components are eliminated through decreasing the harmonic voltage error between PCC and bus of MG. In the islanded MG, the system's harmonic current sharing improvement was provided at the expense of increased voltage harmonic distortion. Thus, the harmonic compensation of islanded MG was calculated using a secondary controller and then sent to VCI at the primary level [16]. Following the same principle, PCC unbalanced depression strategy was considered in [17].

Therefore, in this paper, an active PCC voltage power quality restoring control strategy is proposed based on conventional GCC harmonic suppression controller, the load current of LVDN including linear and non-linear components and the GCC of DCGCM is sampled, and the error is calculated through an additional resonant (R) controller in secondary level. Multiple Park transformation is used to transfer AC harmonic offset signal to DC signal for increasing anti-interference performance. Then the generated voltage harmonic offset is sent to primary level and tracked by VCI. In this way, the required harmonic current is injected into the LVDN to supply the non-linear loads at the cost of slight voltage distortion of DCGCM's output voltage. Therefore, the voltage power quality of PCC can be recovered. At last, the simulation results from SIMULINK/MATLAB have been presented to verify the validity of the proposed control strategy.

This work is organised as follows: Section 2 presents the simplified model of the DCGCM connected to LVDN with nonlinear loads. Section 3 describes the proposed control strategy based on a hierarchical structure. Section 4 presents the simulation results. Section 5 concludes the paper.

2 System modelling

To facilitate the harmonic components analysis of system, assume that there is only one VCI in the DCGCM, and the nth output voltage component of VCI is equivalent to a voltage control source $\left(v_{\mathrm{inv}}^{n\mathrm{th}}\right)$ with an output impedance (Z_{o} (s)), as shown in Fig. 2. The local sensitive loads in MG side and regular loads in the grid side are represented as Z_{mgl} (s) and Z_{gl} (s), respectively. The bus of system is connected to PCC of LVDN through a line impedance (Z_{line} (s)). The ideal grid utility and its equivalent impedance are depicted as $v_{\mathrm{g}}^{n\mathrm{th}}$ and Z_{gequ} (s). It is noted that, the non-linear load of grid side in the model is emulated as the

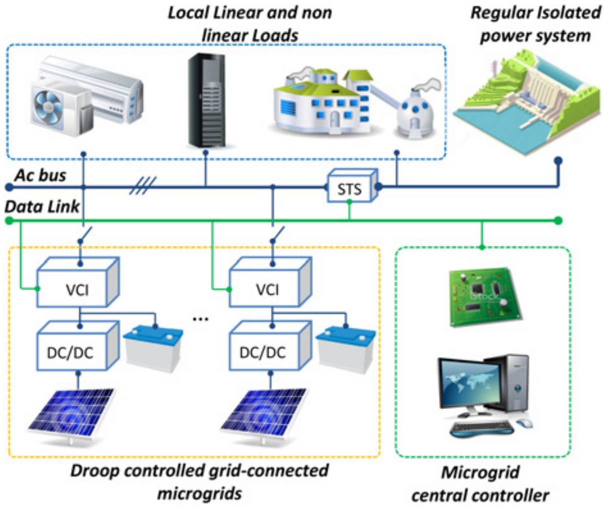

Fig. 1 *Scheme of grid-connecting micro grid with regular and nonlinear loads*

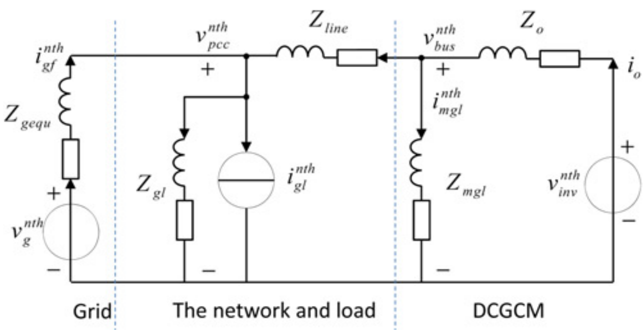

Fig. 2 *Equivalent circuit of system with harmonic current disturbance in the grid side*

harmonic current source $\left(i_{gl}^{nth}\right)$ with different orders and magnitude. Mathematical model can be derived according to Kirchhoff's law

$$\begin{cases} \left(\dfrac{1}{Z_{gequ}+Z_{gl}}\right)v_{pcc}^{nth} - \dfrac{1}{Z_{line}}v_{bus}^{nth} = \dfrac{v_g^{nth}}{Z_{gequ}} - i_{gl}^{nth} \\ \left(\dfrac{1}{Z_o+Z_{mgl}}\right)v_{bus}^{nth} - \dfrac{1}{Z_{line}}v_{pcc}^{nth} = \dfrac{v_{inv}^{nth}}{Z_o} \end{cases} \tag{1}$$

Then, (2) can be derived from (1). It can be seen that the harmonic voltage components of the utility grid and non-linear loads in grid side will influence the output voltage of VCI together

$$v_{inv}^{nth} = \left(\frac{Z_{line}Z_o}{Z_o+Z_{mgl}}\right)i_{gl}^{nth} - \left(\frac{1}{Z_o+Z_{mgl}}\right)\frac{Z_oZ_{line}}{Z_{gequ}}v_g^{nth} \tag{2}$$

3 Proposed PCC voltage power quality restoring strategy based on hierarchical structure

The power flow controller in the tertiary level and synchronisation loop in the secondary level of DCGCM adopted in this paper has been investigated thoroughly in [12–14]. Similarly, the conventional GCC harmonic suppression controller shown in Fig. 3 has been discussed in [15]. However, the main principle of the proposed PCC voltage power quality restoring strategy is control DCGCM to inject proper harmonic current in to the grid to supply nonlinear loads in LVDN. Therefore, two improvements involving harmonic current offset reference generation and tracking are made to the original hierarchical control based DCGCM.

3.1 Secondary level

In order to control DCGCM inject proper harmonic current into the grid, the load current in LVDN and GCC of system is sampled and transferred into the synchronous rotating reference frame with

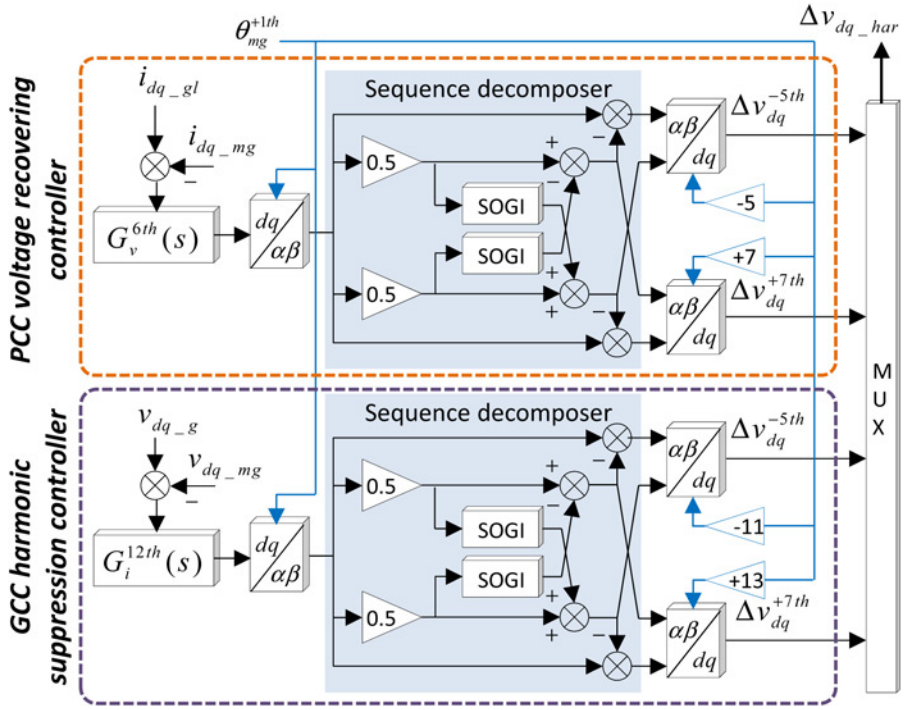

Fig. 3 *Proposed PCC voltage power quality restoring controller*

fundamental angular frequency ω_b. Then, negative 5th components and positive 7th components in current are transferred to 6th trigonometric signal, as shown in Fig. 3. An additional resonant (*R*) controller with resonant angular frequencies of $6\omega_b$ is adopted in secondary level, by which the negative 5th and positive 7th components in *abc* frame will be compensated simultaneously, as shown below

$$G_{\mathrm{v}}^{6\mathrm{th}}(s) = \frac{k_{\mathrm{iv}}^{6\mathrm{th}} s}{s^2 + (6\omega_{\mathrm{b}})^2} \tag{3}$$

where $k_{\mathrm{iv}}^{6\mathrm{th}}$ is the integral parameter of *R* controllers for 6th harmonic components.

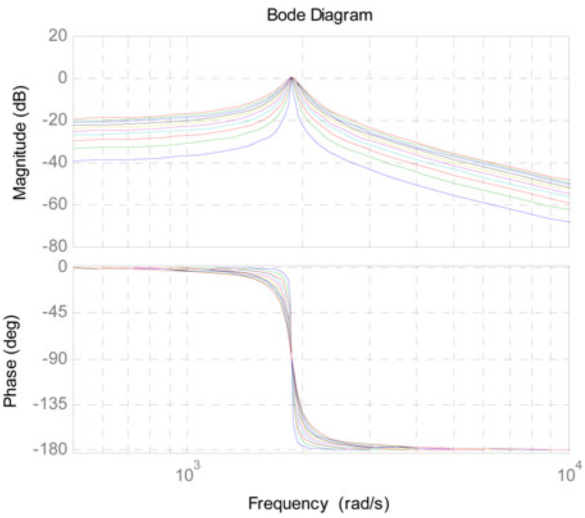

Fig. 4 *The bode of SOGI with different parameters*

Given that the AC offset signal will be more easily interfered when comparing to DC signal; the output of *R* controller is first transformed to the ab frame with the fundamental angular frequency. As positive 6th components and negative 6th components in *ab* frame are mixed, which represents positive 7th and negative 5th components in *abc* frame, respectively, a sequence decomposer is adopted, in which second order generalized integrator (SOGI) is used for one-fourth delay as shown below

$$G_{\mathrm{SOGI}}(s) = \frac{k(6\omega_{\mathrm{b}})^2}{s^2 + 6ks\omega_{\mathrm{b}} + (6\omega_{\mathrm{b}})^2} \tag{4}$$

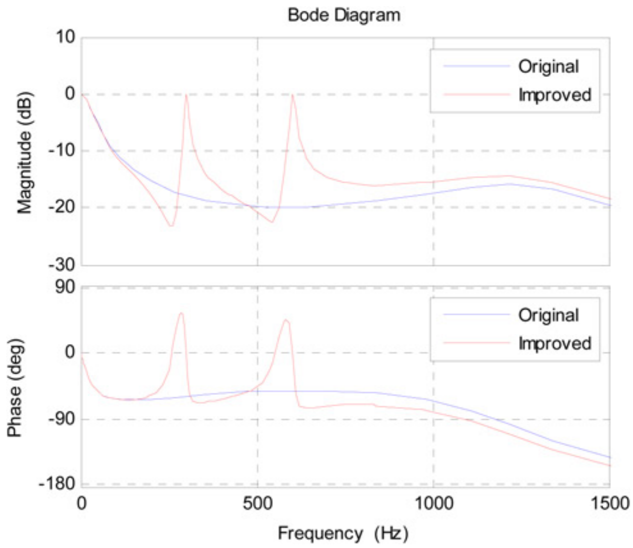

Fig. 6 *Comparing bode of VCI with inner conventional and improved voltage/current control loop*

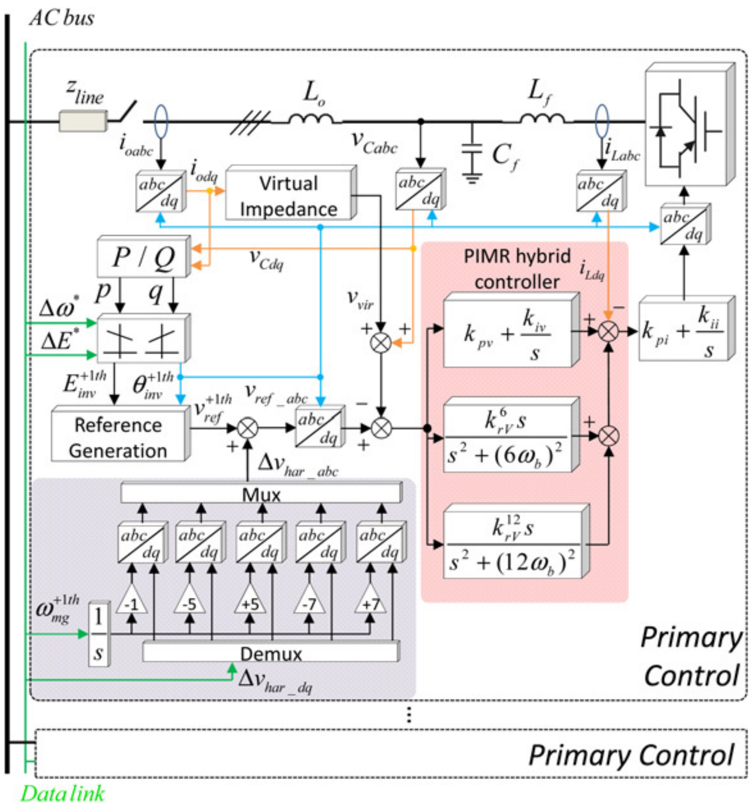

Fig. 5 *Detailed control scheme of VCI in primary level*

Table 1 Parameters of simulation model

	Parameters		Value
	Sym	Description	
electrical circuit	L_f	filter inductance	1.8 mH
	C_f	filter capacitance	9.9 μF
	Z_{line}	kine impedance	0.1 Q Ω + 1.8 mH
linear loads	P_{local}	P of local load of VCI	2000 W
	Q_{local}	Q of local load of VCI	400 Var
	P_{grid}	P of regular load	3000 W
	Q_{grid}	Q of regular load	800 Var
non-linear current disturbance	I^{-5th}	harmonic load current of 5th	2 A
	I^{+7th}	harmonic load current of 7th	1.5 A
	I^{11th}	harmonic load current of 11th	1 A
	I^{+13th}	harmonic load current of 13th	0.6 A
primary			
inner loop	k_{pv}	voltage proportional term	0.04
	K_{iv}^{6th}	voltage integral term of 6th	75
	K_{iv}^{12th}	voltage integral term of 12th	30
	K_{pi}	current proportional term	0.07
secondary			
harmonic compensator	K_{ihv}^{6th}	6th integral term of PCC voltage power quality restoring	10
	K_{iv}^{12th}	12th integral term of GCC power quality restoring	20
grid syncho	$k_{p\omega\_g}$	syn proportion term for ω	5×10^{-3}
	$K_{i\omega\_g}$	syn integral term for ω	5×10^{-5}
	k_{pE_g}	syn proportion term for E	10
	K_{iE_g}	syn integral term for E	0.1
tertiary			
gridfeeding controller	k_{pP}	proportional term for P_{mg}	5×10^{-2}
	K_{iP}	integral term for P_{mg}	5×10^{-1}
	k_{pQ}	proportional term for Q_{mg}	8×10^{-5}
	K_{iQ}	integral term for Q_{mg}	4×10^{-4}

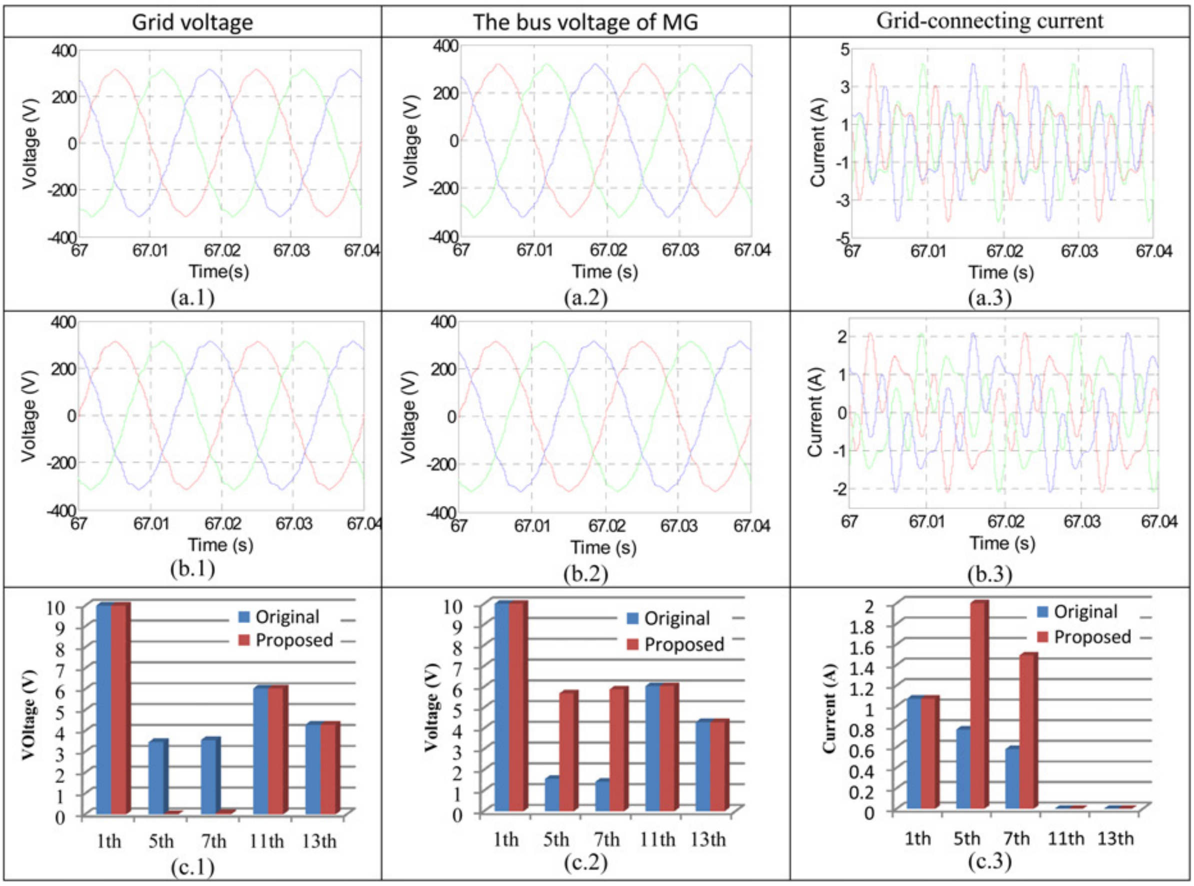

Fig. 7 *Comparing simulation result*

where k is the coefficient affecting the SOGI's bandwidth, as shown in Fig. 4. Then, the decomposed components are transformed to the DC signal by using the Park transformation with the corresponding angular frequency and sequence.

3.2 Primary level

Primary control of DCGCM is responsible for stabilising the frequency and magnitude of the bus voltage, as well as the power sharing between VCIs. The DC offset signal generated in the secondary level is transmitted to the primary level through the low bandwidth communication network, and then transferred back to the *abc* frame ($\Delta v_{\mathrm{har\_abc}}$) with corresponding angular frequency and sequence. The fundamental voltage reference component is generated by the droop controller according to output active/reactive power of VCI as shown in Fig. 5. Therefore, the final three-phase voltage reference can be calculated as follows:

$$\begin{cases} v_{\mathrm{ref\_a}} = E_{\mathrm{inv}}^{+1\mathrm{th}} \sin\left(\theta_{\mathrm{inv}}^{+1\mathrm{th}}\right) + \Delta v_{\mathrm{har\_a}} \\ v_{\mathrm{ref\_b}} = E_{\mathrm{inv}}^{+1\mathrm{th}} \sin\left(\theta_{\mathrm{inv}}^{+1\mathrm{th}} - 2\pi/3\right) + \Delta v_{\mathrm{har\_b}} \\ v_{\mathrm{ref\_c}} = E_{\mathrm{inv}}^{+1\mathrm{th}} \sin\left(\theta_{\mathrm{inv}}^{+1\mathrm{th}} + 2\pi/3\right) + \Delta v_{\mathrm{har\_c}} \end{cases} \tag{5}$$

where $\Delta v_{\mathrm{har\_abc}}$ is the PCC voltage power quality restoring offset in the *abc* frame. $\Delta E_{\mathrm{inv}}^{+1\mathrm{th}}$ and $\Delta \theta_{\mathrm{inv}}^{+1\mathrm{th}}$ are magnitude and phase reference generated by local droop controller, respectively. Obviously, there is fundamental, 6th and 12th harmonic components in the voltage reference. Therefore, a proportional-integral (PI) and multiple-resonant (PIMR) voltage controller is adopted, the comparing magnitude-frequency feature of VCI is shown in Fig. 6. It is can be seen the VCI with PIMR voltage controller can track harmonic reference precisely.

4 Simulation verification

To verify the proposed PCC voltage power quality restoring strategy, the simulation model is established in SIMULINK/MATLAB in which two droop based VCIs, the distorted grid, and the harmonic current source at 5th, 7th, 11th and 13th based non-linear loads are included. The detailed parameters of simulation model are shown in Table 1.

The grid voltage, bus voltage, and GCC of MG with conventional and proposed control strategy are shown in Figs. 7*a*.1–*a*.3 and *b*.1–*b*.3, respectively. It can be seen from Figs. 7*c*.1 and *c*.2 that the negative 11th and positive 13th component of the PCC voltage and MG bus voltage are almost the same, resulting from the well-tuned conventional harmonic GCC compensator. Therefore, there is no harmonic GCC at corresponding angular frequency, as shown in Fig. 7*c*.3. However, the loads disturbance current with negative 5th and positive 7th harmonic components affects the voltage of PCC, and then the corresponding harmonic GCC is injected into the grid without any regulation. When the proposed PCC voltage power quality restoring controller is adopted by system, the negative 5th and positive 7th current of injected GCC of MG is controlled to be increased to 2 and 1.49 A, respectively, in steady state, as shown in Fig. 7*c*.3, and then the corresponding harmonic components of PCC voltage is decreased to around zero effectively, as shown in Fig. 7*c*.1. At the same time, the positive fundamental components, the negative 11th and the positive 13th components of GCC are same as system with only the conventional control strategy.

5 Conclusion

An active voltage harmonic components suppression strategy based on DCGCM is proposed in this paper. The load current of LVDN and the GCC of DCGCM is sampled, and then calculated through an additional PCC voltage power quality recovering compensator adopted in the secondary controller of system. In steady state, the proper harmonic current is controlled and injected into the LVDN through line impedance for supplying the non-linear loads in network at the cost of slight voltage distortion of system's output voltage. Eventually, the simulation result shown the corresponding harmonic voltage component of PCC is suppressed effectively by the proposed compensator.

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